High-Speed Interlaced Spin-Echo Magnetic Resonance Imaging

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A new method is introduced for increasing the efficiency in multislice single spin-echo MRI. The method interlaces the excitation and measurement of different slices, resulting in an effective use of the echo delay time between RF excitation and reception. Under certain conditions, the method allows for scan time reduction compared to standard single spin-echo MRI, in particular for long echo times. The technique is demonstrated in examples of brain scans, indicating that a substantial increase is scan speed can be achieved without loss in image signal-to-noise ratio or contrast. Potential applications include perfusion imaging using T_2-contrast agents, as well as BOLD-based functional imaging. Magn Reson Med 43:905–908, 2000. Published 2000 Wiley-Liss, Inc.†

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Techniques based on single spin-echo acquisition have been widely used in MRI. They allow the generation of T_2-contrast, which is useful in detection of anatomic abnormalities in pathologies such as brain tumors, stroke, and multiple sclerosis. In addition, spin-echo (SE) MRI can be applied for the study of physiology and function using perfusion techniques based on susceptibility contrast agents (1) as well as functional MRI (fMRI) based on blood oxygen level dependent (BOLD) contrast (2). To vary the T_2-contrast, the echo delay time (TE) is adjusted, usually within a range of tens to hundreds of milliseconds. However, with increasing TE, also the repetition time (TR) needs to be increased. At long TEs (and TRs), the single SE technique becomes less efficient, because the time fraction spent with acquiring data is reduced. This leads to an increased scan time, or a signal-to-noise ratio (SNR) that is suboptimal.

To increase efficiency in SE MRI, techniques have been proposed to generate a number of spin-echos per excitation (3-5). These echos can be combined in various ways to generate maps of T_2 time constants (4), reduce scan time (5), or simply increase SNR (3). For the latter two applications, however, because the T_2-weighting varies between the echoes, optimal T_2-contrast is often achieved for only a small number of the echo signals. For example, when strong T_2-contrast is desired, echoes acquired at the shorter TEs do not convey much of the desired information. In addition, T_2-decay over the echo train can result in significant image blurring (T_2-blurring), in cases where the echoes sample different parts of *k*-space. In the following, an alternative scan approach is presented that improves efficiency over SE MRI, while acquiring only a single spin-echo at the desired echo time. This approach is a variant of the earlier introduced TE-interleaved multislice technique (6), which has somewhat different tradeoffs.

METHODS

The basic concept of the new SE method is to interlace RF pulses and acquisitions of successive slices. The advantage over a standard SE sequence is that part of the delay time between excitation and reception of a specific slice is used to acquire data from other slices. This interlacing technique, similar to the use of echo-shifting (7) in multislice gradient echo imaging (8), effectively 'compacts' the sequence. A prerequisite for useful application is that the duration of the slice selection is significantly shorter than the data acquisition interval. Two main variants can be distinguished between the possible implementations: one in which the echo is acquired after a 90° pulse, and one in which the echo is acquired after a 180° pulse, as in conventional SE MRI.

In the simplest implementation of the first variant (Fig. 1a), interlacing is performed by moving the excitation pulse of the following slice (n + 1) in between the refocusing pulse and data acquisition of the current slice (n). This scheme allows for a 50% speed increase compared to conventional SE. Larger gains can be achieved when TEs are sufficiently long to allow extension over more than one TR_{IS} interval (here and in the following TR_{IS} indicates the interval between two successive 90° pulses unless otherwise stated). Delays over any desired *odd* number of TR_{IS} intervals can be achieved simply by adjusting the lookup tables for the RF excitation frequencies.

An example of the second variant, with data acquisition after a 180° pulse, is given in Fig. 1b. In this example, the 90° pulse from the following slice (slice n + 1) is now moved up into the 90° to 180° interval of the current slice (slice n). This allows for the measurement of two additional slices (n-1 and n-2) in the delay time between excitation and acquisition of slice n. With this variant, delays over any desired *even* number of TR_{IS} intervals can be achieved.

For all implementations, a prerequisite for proper echo formation is adequate spoiling of the FID signal, as well as full refocusing of the desired echo signal. This can be achieved by using additional dephaser/rephaser gradients (G_{add}) with strength relationship b = c for the first variant (see Fig. 1a), and a = b for the second variant (see Fig. 1b), and a, b, and 2a + c all exceeding 2π/voxel. In addition, the gradients associated with the slice select gradients (for both excitation and refocusing pulse), as well as the imaging gradients (e.g., read and phase encode) need to be refocused, i.e., have a net integral equal to 0.

With both variants, symmetric spin-echoes can be generated when using RF pulse spacings of 1/3 and 2/3 TR_{IS}.

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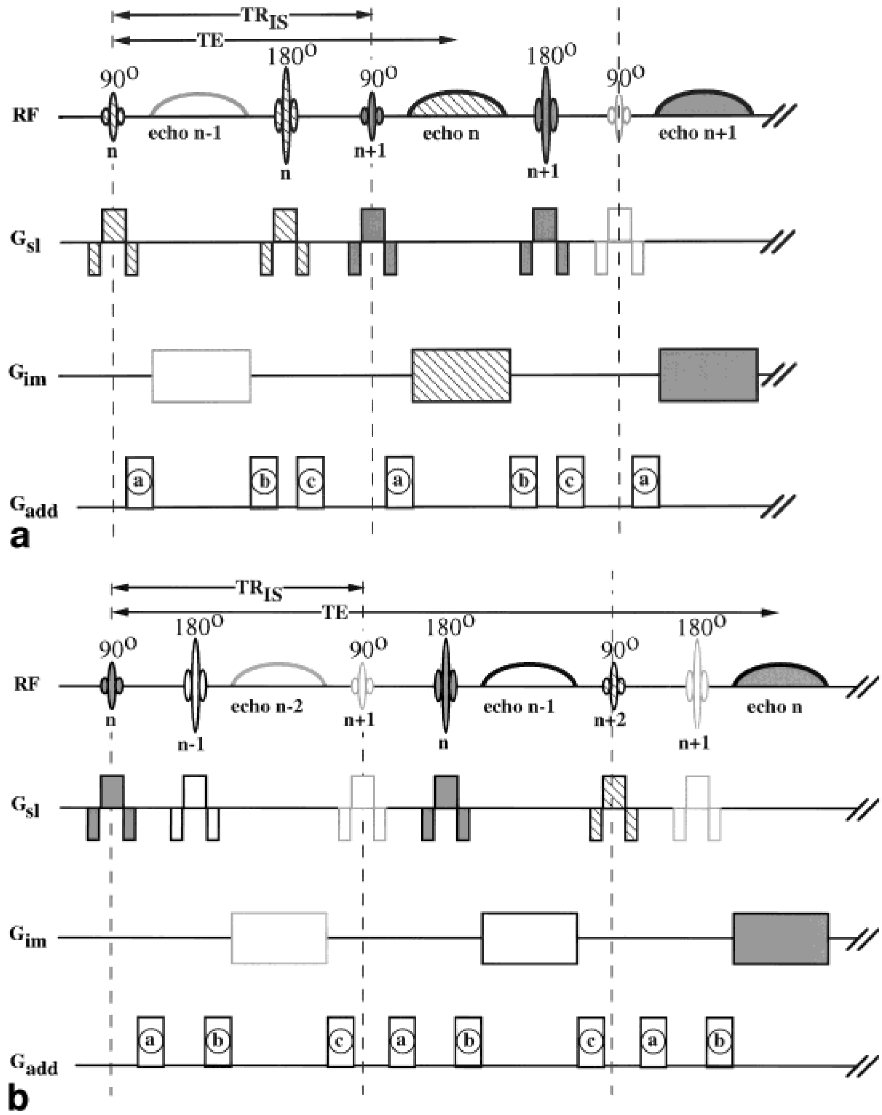

FIG. 1. **a:** Interlaced spin-echo imaging with signal reception after the 90° pulse of a subsequent slice (signal reception occurs during application of G_{im}). TE indicates the echo delay time, whereas TR_{IS} indicates the 90°–90° interval, equivalent to the effective measurement time per slice. The interlacing scheme allows effective use of the delay time between excitation and refocusing pulse. In order to suppress unwanted signals, e.g., FID signals from the 90° and 180° pulses, additional gradient dephasers and rephasers (**a**, **b**, and **c**) are used. In addition, slice select (G_{sl}) and imaging gradients (G_{im}) are fully refocused. **b:** Interlaced spin-echo imaging with signal reception after a 180° pulse of a subsequent slice. The spin-echo is delayed over two TR_{IS} (i.e., 90°–90°) intervals. As in the variant given in **a**, three additional gradient dephasers and rephasers (**a**, **b**, and **c**) are used. Again, slice select (G_{sl}) and imaging gradients (G_{im}) are fully refocused.

In the examples of Fig. 1, all of the longer intervals (2/3 TR_{IS}) are used for data acquisition, suggesting that in the ideal case of infinitely short RF and gradient pulses, the efficiency of the technique with regards to time utilization approaches 67% of theoretical maximum. Other pulse spacings might result in higher efficiencies, however, they will lead to echoes that are not centered in the measurement interval. This is not necessarily problematic, in fact, some fMRI applications rely on the additional T_2^* weighting provided with asymmetric spin-echo acquisition.

Both standard SE and interlaced SE (or ISE) protocols were implemented on a 1.5 T clinical scanner (GE Medical Systems, Milwaukee, WI), equipped with 22 $mT \cdot m^{-1}$, actively shielded whole-body gradients with a maximum slew rate of 120 $T\ m^{-1}\ s^{-1}$. A standard quadrature head RF coil was used for measurement on phantoms and human brain. The human subject protocol was approved by the intramural review board of the National Institutes of Health. Two image acquisition techniques were used for both SE and ISE methods: a standard spin-warp technique with phase encode and readout gradients, as well as a single-shot spiral scan technique with trapezoidal gradients (9). The field of view was 240 mm, slice thickness 4 mm. For the spin warp technique, a matrix size of 256 × 128 was used, with a data acquisition window of 4 msec, and TE = 80, TR_{IS} = 90 msec for the SE version. An ISE implementation, variant 1 (Fig. 1a), was used with TE = 80, TR_{IS} = 60. The number of slices was 24 (SE) resp. 36 (ISE), resulting in an overall (volume) TR of 2.2 sec. For the single-shot spiral scan technique, a matrix size of 64 × 64 was used, and a data acquisition window of 22 msec, and TE = 120, TR_{IS} = 150 msec for the SE version. The ISE version, used TE = 120, TR_{IS} = 90 (variant 1) and TE = 240, TR_{IS} = 90 (variant 2). The number of slices was 36 for all spiral scans. Crusher gradients a, b, and c (see Fig. 1) were applied in slice select direction and one image axis simultaneously, with effective strengths of 8π/cm. For all experiments, sinc-gauss RF pulses were used with 2 sinc sidelobes. The slices were acquired in an interleaved fashion (1,3,5,7 . . . 2,4,6,8 . . .) to reduce slice profile interactions.

RESULTS AND DISCUSSION

Figures 2 and 3 show results of ISE implementations for the spin-warp and the spiral imaging techniques respec-

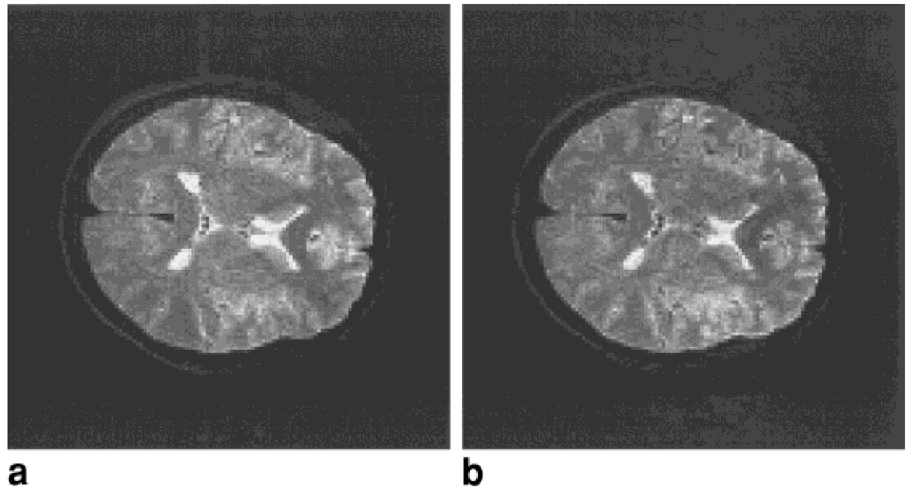

FIG. 2. Example of an ISE implementation in spin-warp imaging. A single brain slice is displayed out of a multi-slice dataset acquired without (**a**) and with (**b**) interlacing. While preserving image contrast, ISE allowed for a 50% increase in scan speed. Some increase in streaking artifacts was also observed with ISE, and attributed to increased motion sensitivity.

tively. With the spin-warp technique (Fig. 2), standard spin-echo (Fig. 2a) and ISE variant (Fig. 2b) resulted in similar (less than 5% difference) SNR and image contrast, indicating the effectiveness of the ISE technique at reducing scan time without sacrifice in T_2-weighting. However, an increased amount of streaking artifacts was observed with the ISE variant. This was attributed to the increased sensitivity to motion related signal phase variations, caused by the additional gradient pulses associated with interlacing. These artifacts could likely be reduced by the use of phase corrections based on navigator echoes.

The implementation of standard SE and ISE with spiral imaging (Fig. 3) again showed that contrast and SNR was maintained with ISE. In addition, the flexibility of ISE to manipulate T_2 contrast without changing TR_{IS} was demonstrated by implementation of variant 2 (Fig. 3c). Con-

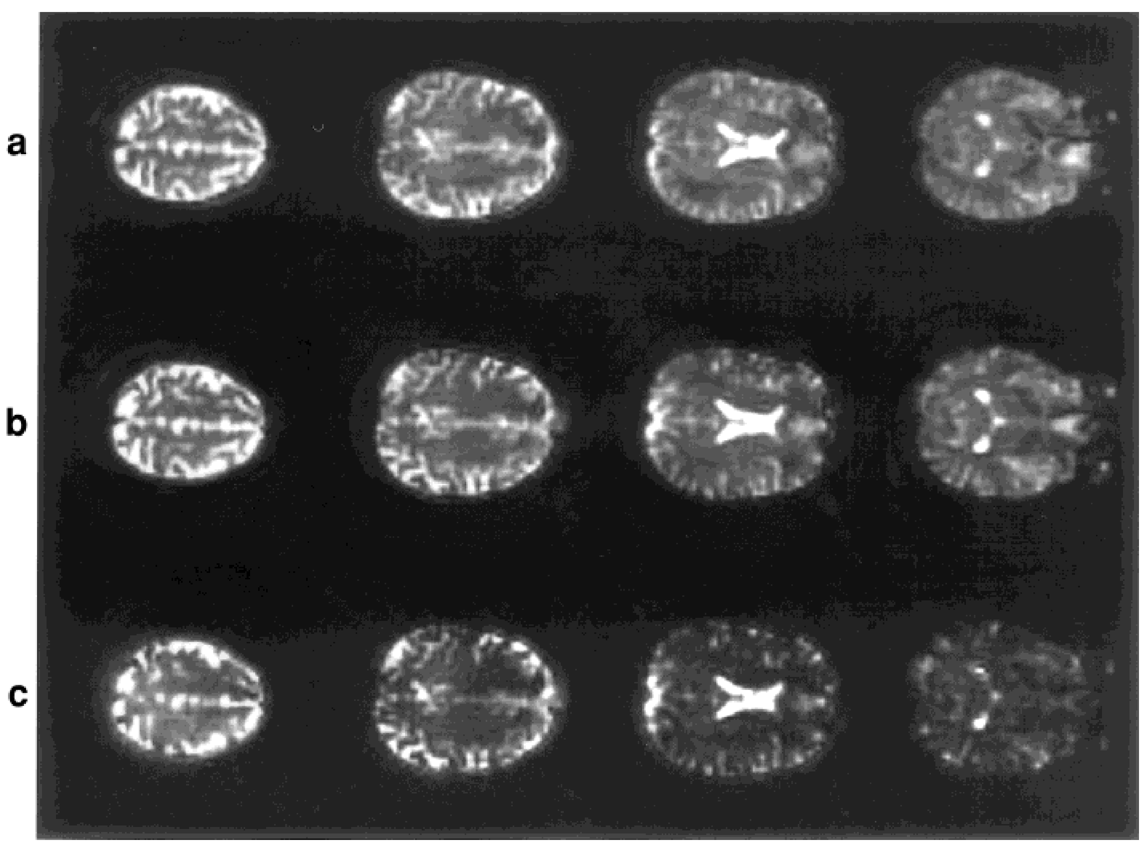

FIG. 3. Example of an ISE implementation in spiral imaging. Four brain slices are displayed out of a 36-slice datasets acquired without (**a**) and with (**b**, **c**) interlacing. For the standard SE data (**a**), TE = 120 msec was used. For the ISE data, both variant 1 (**b**) and variant 2 (**c**) were used, with TE = 120 msec and TE = 240 msec, respectively. Note the similarity in image contrast between **a** and **b**, and the increased T_2-weighting in **c**.

trary to the spin-warp experiments, ISE combined with spiral imaging did not lead to an increased level of artifacts. This is attributed to the fact that single-shot techniques such as spiral imaging, are insensitive to motion related phase variations over pulse repetitions (TR intervals). In addition, with the particular application of single-shot imaging, there appears to be some efficiency advantage of ISE over the TE-interleaved multi-slice technique (6), because of the long duration of the readout window relative to the RF pulse lengths.

Potential applications of ISE are experiments that require significant T_2-weighting, such as diagnostic imaging, BOLD-based functional imaging, and perfusion imaging based on bolus-tracking with susceptibility contrast agents. In particular in situations in which TE is significantly longer than the duration of the acquisition (readout) window, and the RF and crusher pulse durations are relatively short, substantial time savings can be achieved over standard SE. A disadvantage of the proposed method, as with other single spin-echo methods, compared to FSE, is the reduced SNR. In addition, ISE limits the flexibility in choosing the number of slices in combination with TE and TR_{IS} values, and the inability to accommodate contrast preparation sequences such as inversion pre-pulses for outer-volume or lipid saturation or T_1-weighting.

CONCLUSION

A new method to increase efficiency in single spin-echo MRI was designed and evaluated on human brain. The method appears advantageous in MRI applications that require long echo times, in particular when combined with single-shot acquisition methods such as EPI or spiral imaging.

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